LAMS-2532 (Vol. I)
SPECIAL DISTRIBUTION

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT WRITTEN: 1946 and 1947

REPORT DISTRIBUTED: December 1, 1961

MANHATTAN DISTRICT HISTORY
PROJECT Y
THE LOS ALAMOS PROJECT

VOL. I. INCEPTION UNTIL AUGUST 1945

by

David Hawkins

VOL. II. AUGUST 1945 THROUGH DECEMBER 1946

by

Edith C. Truslow
and
Ralph Carlisle Smith

Contract W-7405-ENG. 36 with the U. S. Atomic Energy Commission

This LAMS report has been prepared because of the demand for and interest in the historical information. The two volumes have not been edited except for classification purposes nor verified for accuracy. All LAMS reports express the views of the authors as of the time they were written and do not necessarily reflect the opinions of the Los Alamos Scientific Laboratory or the final opinion of the authors on the subject.

a neutron may be absorbed, scattered, or produce fission. The contributions of each process are measured by the corresponding cross sections, or effective target areas presented by the nucleus to an impinging neutron. The total cross section is divided into areas that win, lose, or draw (fission, absorb without fission, or scatter), these areas corresponding to the relative probabilities of the three processes. If the scattering is not isotropic, it is also necessary to specify the angular distribution of scattered neutrons. All of these cross sections, moreover, depend upon the nucleus involved and the energy of the incident neutron. Calculation of critical mass and efficiency depends upon all of these cross sections, as well as upon the number of neutrons per fission and density of material. It was clear that to obtain such measurements with the necessary accuracy would entail an elaborate program of experimental physics and a comparable effort of theoretical physics to make the best use of information obtained.

1.37 Effects of Tamper. The effect of tamper is not only to decrease the critical mass by reflecting neutrons back into the active material, but also to increase the inertia of the system and therefore the time during which it will remain in a supercritical state. These gains are somewhat lessened by the longer time between fissions of neutrons reflected back from the tamper. The lengthening of the time is caused not only by the longer path, but also by a loss of energy through inelastic scattering in the tamper. Calculations of the effect of tamper material depend thus on the absorption and scattering cross sections of tamper material. It is interesting to note that Serber's early calculations gave, for a tamper of U^{238}, a critical mass for U^{235} of 15 kilograms, and for Pu^{239} of 5 kilograms. Both figures are correct to within a reasonable error. This may be regarded as in part good fortune, since many of the assumption made were rough guesses. It nevertheless serves to illustrate the advanced state of basic theory at the time.

1.38 Efficiency, Detonation, and Predetonation. Some indication has been given above of the basis for efficiency calculations. The outcome of such calculations was to show that efficiencies would be low. There is, moreover, another essential factor in efficiency, connected with the problem of assembly and detonation, the early discussion of which is reviewed below.

1.39 It is inherent in the nature of explosive reactions that they can be set off by relatively minute forces, the requirement being, in general, a disturbance sufficiently great to initiate some type of chain reaction. Chemical explosives can be protected with greater or less certainty from such external forces as may initiate a reaction. A supercritical mass of nuclear explosive, however, cannot be protected from "accidental" detonation. Chain reactions will begin spontaneously with greater certainty than in the most unstable chemical compounds. Cosmic ray neutrons will enter the mass from outside. Others will be generated in it from the spontaneous fissions that constantly occur in uranium and plutonium. Still others come from nuclear reactions, most importantly from the (α, n) reaction in light element impurities. The problems presented by this "neutron background" are responsible for a considerable part of the project's history. From the first and weakest source alone (cosmic rays) any supercritical mass will be detonated within a fraction of a second, from other unavoidable sources within a very much shorter time.

1.40 The only method for detonating a nuclear bomb is, therefore, to bring it into a supercritical configuration just at the time when it is to be detonated. The required speed of assembly depends upon the neutron background. As the parts of the bomb move together, the system passes smoothly from its initial subcritical to its final supercritical state. Chain reactions may, however, set in at any time after the critical position has been reached. If the velocity of assembly is small compared to the rate of the nuclear chain reaction, and if predetonation occurs, the explosion will be over before assembly for maximum efficiency has occurred. Thus the explosion may occur, with a widely varying range of efficiencies, at any time between the critical and the final supercritical positions. To decrease the probability of predetonation and consequent low efficiencies requires either a higher speed of assembly or a lower neutron background.

1.41 Gun Assembly, Initiator. The considerations of the last section indicate the magnitude of the assembly problem: to initiate properly and reliably a reaction whose entire course occurs in a fraction of a microsecond, subject to the complementary needs for high velocity assembly and low neutron background. As was mentioned above, the principal source of neutron background is the (α, n) reaction in light-element impurities. To lower this background would require a strenuous program of chemical purification.

1.42 The most straightforward early proposal for meeting these difficulties was the method of gun assembly; the general proposal was that a projectile of active and tamper material, or of active material alone, be shot through or laterally past a target of active material and tamper. For U^{235} both the chemical purity requirements and the needed velocity of assembly were attainable by known methods. Many difficult engineering problems were evidently involved, but they did not appear as insuperable. For Pu^{239} the requirements for purity and speed were both somewhat beyond the established range. It seemed, however, that by rather heroic means they could be met.

1.43 High velocity assembly and the reduction of the neutron background would decrease the probability of predetonation; they would also decrease the probability of detonation at the desired time. Unless material could be assembled so as to remain in its optimum configuration for a considerable length of time, there was a danger that "postdetonation" too would give low efficiency, or that the system would pass through its supercritical state without detonation occurring at all. To overcome this difficulty it would be necessary to develop a strong neutron source that could be turned on at the right moment. Theoretically feasible schemes for such an initiator had been conceived, but their practicability was not assured.

1.44 Autocatalysis, Implosion. Two other methods of assembly had been proposed, and it was a part of the early program to investigate them. One of these was a self-assembling or autocatalytic method, operating by the compression or expulsion of neutron absorbers during the reaction. Calculation showed that this method as it stood would require large quantities of material and would give only very low efficiencies.

1.45 The second alternative method was that of implosion.

1.46 The Deuterium Bomb or "Super." There existed, at the time of the April Conference, one other important proposal to which considerable thought and discussion had been given in the previous months. This was a proposal to use the fission bomb as a means for initiating a nuclear reaction of a different type from that involved in the fissioning of heavy-element nuclei. Fissioning, the disruption of nuclei with liberation of energy, is a somewhat anomalous reaction restricted to the heaviest nuclei. Among the lighter elements the typical exoergic (energy-producing) reaction is the building up of heavier nuclei from lighter ones. For example, two deuterium (H^2) nuclei may combine to form a He^3 nucleus and a neutron, or a tritium nucleus (H^3) and a proton. The energy that is liberated goes into kinetic energy and radiation. If such a reaction occurs in a mass of deuterium, it will spread under conditions similar to those that control ordinary thermochemical reactions. Hence the reaction is called thermonuclear. The cross section for a reaction between two deuterium nuclei is strongly dependent upon the energy of the nuclei. At low energies the probability that the reaction will occur is very small. As the temperature of the material increases, the reaction becomes more probable. Finally a critical temperature is reached, where the nuclear reactions in the material just compensate for various kinds of energy loss, such as heat conduction and radiation. The thermonuclear reaction is in detail more complicated than has been indicated, because of the presence of a variety of secondary reactions.

1.47 Among available materials, deuterium has the lowest ignition temperature. This temperature was estimated to be about 35 kilovolts (about 400 million degrees), and is actually somewhat lower. Once ignited, deuterium is about 5 times as energy-productive per unit mass as U^{235}. Thus 1 kilogram of deuterium equals about 85,000 tons of TNT equivalent. Since it is not more difficult to ignite a large than a small mass of deuterium, and since it is more cheaply produced in usable form than either U^{235} or Pu^{239}, the proposed weapon, using a fission bomb as a detonator and deuterium as explosive, could properly be called an atomic super-bomb. The development of this super-bomb was perforce secondary to that of the fission bomb; on the other hand its potentialities were so great that research toward its development could not be completely neglected.

1.48 It should be mentioned at this point that in the early period of the project the most careful attention was given to the possibility that a thermonuclear reaction might be initiated in light elements of the Earth's atmosphere or crust. The easiest reaction to initiate, if any, was found to be a reaction between nitrogen nuclei in the atmosphere. It was assumed that only the most energetic of several possible reactions would occur, and that the reaction cross sections were at the maximum values theoretically possible. Calculation led to the result that no matter how high the temperature, energy loss would exceed energy production by a reasonable factor. At an assumed temperature of three million electron volts the reaction failed to be self-propagating by a factor of 60. This temperature exceeded the calculated initial temperature of the deuterium reaction by a factor of 100, and that of the fission bomb by a larger factor.

1.49 The impossibility of igniting the atmosphere was thus assured by science and common sense. The essential factors in these calculations, the Coulomb forces of the nucleus, are among the best understood phenomena of modern physics. The philosophic possibility of destroying the earth, associated with the theoretical convertibility of mass into energy, remains. The thermonuclear reaction, which is the only method now known by which such a catastrophe could occur, is evidently ruled out. The general stability of matter in the observable universe argues against it. Further knowledge of the nature of the great stellar explosions, novae and supernovae, will throw light on these questions. In the almost complete absence of real knowledge, it is generally believed that the tremendous energy of these explosions is of gravitational rather than nuclear origin.

1.50 More immediate and less spectacular global dangers to humanity arise from the use of thermonuclear bombs, or even fission bombs, in war: principally from the possible magnitude of destruction and from radioactive poisoning of the atmosphere (13.14).

1.51 Damage. So far we have reviewed only the early discussion of energy release. Since, however, the purpose of the project was to produce an effective weapon, it was necessary to compare the atomic bomb with ordinary bombs, not merely as to energy release, but more concretely as to destructive effects. Damage could be classified under several headings: The psychological effects of the use of such a weapon; the physiological effects of the neutrons, radioactive material and radiation produced; the mechanical destruction produced by the shock wave of the explosion. Estimation of the first was not of course within the means or jurisdiction of the project. Of the second, it was estimated that lethal effects might be expected within a radius of 1000 yards of the bomb. The radioactivity remaining might be expected to render the locality of the explosion uninhabitable for a considerable period, although this effect would depend on the percentage of activity left behind, which was as yet an unknown quantity. The principal damage would be caused by the mechanical effects of the explosion. These effects were difficult to estimate. Some rough data on the effects of large explosive disasters were available. More reliable information was available concerning the effects of small high explosive bombs, but it was not known for sure how these effects should be scaled upward for high energy atomic bombs. Serber's report gives an estimate of a destruction radius of about 2 miles for a 100,000 ton bomb. Members of the British mission who came to the project somewhat later were able to add to the understanding of this topic from their national experience and their research of recent years.

DEVELOPMENT OF PROGRAM

Introduction

1.52 From the previous outline of the state of knowledge at the beginning of Project Y, it is clear that the greatest problems were bound to arise on the side of development and engineering. There was still much work to be done in nuclear physics proper, but enough was known to eliminate great uncertainties from this side of the picture. It should not be concluded, however, that the stage of research was past its prime, to be dominated in turn by problems of application. The normal meanings attached to "research," "development," and "engineering" are altered in the context of wartime science generally; that is particularly true of the atomic bomb project. Two features have determined its general character. The first is the domination of research schedules by production schedules; the second is the nature of the weapon itself. Time schedules for the production of U^{235} and Pu^{239} were such that the laboratory had before it about two years until explosive amounts of these materials would be available. After that time every month's delay had to be counted as a loss to the war. The practical purified at a special plant. Aside from research on polonium, the other main activity of the radiochemists in the summer of 1944 was the design and construction of a "mechanical chemist," a remote control plant for extracting and handling the highly radioactive radio-lanthanum to be used at the Bayo Canyon RaLa site.

The Discovery of Pu^{240}

4.42 There is perhaps no better illustration of the interconnection of research and development at Los Alamos than the series of developments that led to the discovery of the 240 isotope of plutonium in the Clinton product. As was mentioned above (4.1) there was room for doubt as to the value of plutonium as bomb material, up to the time when, in the summer of 1943, its neutron number was first measured. Even with the favorable result of this measurement there were still serious difficulties: from 1 gram of plutonium there are 2×10^9 alpha particles emitted per second. To keep the neutron background from (α, n) reactions down to the level where fast gun assembly was feasible required high purity; in the case of three light elements, less than one part per million.

4.43 Spontaneous fission measurements had been undertaken first at Berkeley, for the direct purpose of ascertaining the neutron background from this source of U^{235}. At Los Alamos these measurements were refined and extended to Pu^{239} and other materials. In the summer of 1943, meanwhile, there came through from France a report that Joliot had found a neutron emission associated with the alpha radiation of polonium, but not coming from the action of this radiation on light element impurities. Although this report was not believed correct, it was recorded in the Minutes of the Governing Board, and the general intention stated of looking into all the questions connected with spontaneous neutron emission.

4.44 As a result of the Joliot report, work was begun to develop highly sensitive neutron counters, and a radon plant was obtained. The reason for the latter was that radon was the alpha emitter which could be most highly purified. If it was found that there was heavy neutron emission from alpha emitters as such, this might make a modulated initiator impossible. It might also mean a prohibitively high neutron background in plutonium itself.

4.45 As the spontaneous fission measurements increased in reliability, it was found that the spontaneous fission of plutonium was slow enough to make the neutron background from this source not serious. In the meantime, however, another piece of research entered into the story. Fission cross section measurements at low energies, whose programmatic justification was to obtain data to be used in calculating the uranium hydride critical mass, showed the presence of resonances in the U^{235} fission absorption spectrum. This led, for theoretical reasons, to the expectation of sizable radiative neutron capture. In the case of Pu^{239}, this meant the production of a new isotope, Pu^{240}. Since this isotope would be produced by the absorption of two neutrons in U^{238}, its concentration in the pile plutonium would go up with heavier irradiation.

4.46 In the summer of 1944, therefore, when the first Clinton plutonium made by chain reactor arrived - much more heavily irradiated than the previous samples made by cyclotron bombardment - the existence of Pu^{240} was verified, as was the fear that it might be a strong spontaneous fissioner. Neutron background in the plutonium which would be produced at full power was pushed up into the region where, to prevent predetonation, assembly velocities would have to be much greater than those possible with the plutonium gun.

4.47 The only alternative to abandoning the gun method for plutonium was to find means of separating out the offending isotope. This would mean another major investment in separation plant, and could hardly be accomplished within the time alloted before military use. The implosion was the only real hope, and from current evidence a not very good one. Nevertheless the Laboratory had at this time strong reserves of techniques, of trained manpower, and of morale. It was decided to attack the problems of the implosion with every means available, "to throw the book at it." Administratively, the program was taken out of the Ordnance Division, and divided between two new divisions. One of these was to be concerned primarily with the investigation of implosion dynamics, the other primarily with the development of adequate HE components. And this story marks the beginning of the second part of the present history.

The Water Boiler

4.48 The implication of gloom at the fate of plutonium gun method and the difficulties of the implosion do not misrepresent the atmosphere of the Laboratory in the spring and summer of 1944. Yet the program was many sided; during this same period the Laboratory enjoyed its first major success. This was the operation of the Water Boiler to produce divergent chain reactions. This was first accomplished on May 9, 1944, and from this time until August a number of experiments were carried out to determine nuclear

Chapter V

THEORETICAL DIVISION

Organization

5.1 The broad purpose for which the Theoretical Division was formed, as had been said (1.54-1.56), was to develop nuclear and hydrodynamical criteria relating to the design of the atomic bomb, and to predict the detailed performance of the weapon designed. At the beginning the bulk of the division's effort, accordingly, was devoted to the investigation of two closely related key problems: the calculation of the critical mass and the nuclear efficiency.

5.2 The first organization of the division centered around these problems. With the rise of the implosion to prominence the organization of the division, under H. A. Bethe as Division Leader, was formalized into groups as follows (beginning March 1944):

T-1	Hydrodynamics of Implosion, Super	E. Teller
T-2	Diffusion Theory, IBM Calculations, Experiments	R. Serber
T-3	Experiments, Efficiency Calculations, Radiation Hydrodynamics	V. F. Weisskopf
T-4	Diffusion Problems	R. P. Feynman
T-5	Computations	D. A. Flanders

5.3 During June 1944, R. Peierls took charge of the Implosion Group in place of E. Teller who formed an independent group outside the Theoretical Division (13.3). This group acquired full responsibility for implosion IBM calculations. During July 1944 Group O-5 (E-8, 7.1) joined the Theoretical Division on a part time basis, its work in the Ordnance Division being largely completed (14.1).

The Gun

5.17 Critical mass calculations for the gun assembly were complicated primarily by the odd shape of the assembly. The critical mass problem for the gun was not only that of estimating the number of critical masses in the completed assembly, but also of estimating the amount of active material that could safely be disposed in the two parts before assembly. It was also necessary to know how the system went from its initial subcritical to its final supercritical position, in order to be able to calculate the probability of predetonation. The early rough specifications for the gun had been based on critical mass estimates from differential diffusion theory. By February 1944, there was pressure from the Ordnance Division to obtain more reliable specifications, and at this time sufficiently accurate calculations had been made so that, for the U^{235} gun, Group T-2 specified the actual bore. The specification of the gun for the Pu^{239} assembly was reached a short time later. The same group was able to give essentially complete specifications by the summer of 1944 for both gun assemblies, fortunately after cross-section measurements by the Detector Group had resulted in slightly lower average values for U^{235} than those used in earlier calculations.

The Implosion

5.18 The history of theoretical implosion studies lies mostly outside the Theoretical Division until the Fall of 1943. The idea of something like an implosion, as an alternative to gun assembly, had entered several heads before the beginning of Los Alamos. Its first history at Los Alamos belongs mainly to the Ordnance Division, where the initial calculations of attainable assembly velocities were made.

5.19 The Theoretical Division entered the picture when the fast implosion was proposed by von Neumann, and its potentialities as a weapon qualitatively superior to the gun were appreciated. The general story of this development is told in Chapters 7, 15 and 16. Here the emphasis will be upon the theoretical problems that were involved. Implosion studies were the responsibility of Group T-1, with the assistance of other groups, particularly T-2.

5.20 The first problem attacked was that of the time of assembly when (as proposed by von Neumann) large amounts of explosive were used. In this case, the energy required for the work of plastic deformation was small compared to the total energy of the explosive, so that to a first approximation the kinetic energy of the mass moving inward could be assumed to be conserved.

5.21 The numerical solution of the partial differential equation describing the implosion was too difficult for hand calculation with the computing staff available at Los Alamos, when a realistic equation of state was employed. As a result the first effort made was to find simpler approximate equations of state. The first method was based on a multiphase model, in which the state of the imploding material was assumed to change discontinuously. A considerable amount of effort was put into the multiphase model, but the results proved very difficult to interpret.

5.22 Some time was gained in solving this calculational problem by virtue of the fact that IBM machines had already been ordered by the division, with the original intention of using them for the difficult calculations of critical masses of odd-shaped bodies. These machines arrived in the first part of April 1944, and in the meantime preparations had been under way for numerical integration of the hydrodynamical equation by means of them. Preliminary calculations had to be made to determine the initial conditions at which to start the IBM calculations. It was necessary to derive the equation of state of uranium at high pressures, a calculation based on the Thomas-Fermi model of the atom. Results at low pressures were obtained from experimental data of P. W. Bridgman, and the intermediate region determined by interpolation.

5.23 The first results of IBM calculation of the implosion were extremely satisfactory. As a result the unrealistic multiphase implosion model was dropped.

5.24 Just at the time of these first IBM results, a new problem arose which brought the work of the division into closer connection with experimental implosion studies going on at the time. Calculations of implosion dynamics had started with the initial condition of an inward-moving spherical shock wave. But the creation of such a wave had so far proved impossible to achieve. The rather erratic results obtained from multipoint detonations, and in particular the observation of jets, directed theoretical attention to the problem of interference of detonation waves. It was found that a diverging spherical wave will accelerate materials less rapidly than a plane wave, and still less rapidly than a converging wave. In an implosion with many detonation points, the explosive waves are divergent to start with, but it had been assumed that their interaction would make them convergent. When this question was examined theoretically, it was immediately discovered that this smoothing out was by no means assured, and that the fact to be concerned about was the development of high pressure at the point where detonation waves collided. The most obvious method of avoiding these difficulties was to employ explosives so arranged that they would produce converging waves to start with. The use of such lens configurations had just been suggested at this time by J. L. Tuck, and the above observation on shock interactions was an argument in favor of its adoption. It was, however, a completely untried and undeveloped method, which no one wished to employ unless it became absolutely necessary to do so.

5.25 Another important hydrodynamical principle was brought to bear on the problems of implosion by the first visit to the Laboratory of G. I. Taylor in May 1944. He presented arguments to show that an interface between light and heavy material is stable if the heavy material is accelerated against the light material and unstable in the opposite case. This created the possibility of serious instability in the implosion, where light high explosive would be pushing against heavier tamper material, or where a light tamper might be pushing against the heavy core. A similar difficulty, leading to mixing, was also foreseen in the nuclear explosion, as the core became less dense on expanding against the compressor tamper.

5.26 From these two developments there started a trend of thought that radically altered the whole implosion program. From the IBM results the behavior of the symmetric implosion was soon rather completely understood. But at the same time it became more and more doubtful whether a symmetric implosion could be achieved. Thus it was that in the remainder of the year the design of the explosive charge moved in the more radical direction represented by the lens program, while the design of the inner components moved in a more conservative direction.

5.27 As a result of calculations on the development of asymmetry, it was possible to give the Explosives Division a preliminary statement of the asymmetry that could be tolerated. A variation in velocity by 5 per cent was considered the maximum allowable.

5.28 During the remainder of the period under review, more IBM and associated calculations were made, the stability studies referred to above were continued, and calculations were undertaken to determine the shape of lenses to convert the detonation wave to a plane or spherically convergent form. The possible need for various corrections to the simple theory - borrowed from geometrical optics - were also considered.

Efficiency

5.29 The calculation of efficiency was perhaps the most complex problem that the Theoretical Division had to face. The theory of efficiency had to follow the neutron chain reaction and neutron distribution in the bomb, in a medium of fissionable and tamper material that was itself being rapidly transformed by the reaction in both its nuclear and dynamic properties. Every factor involved in the critical mass calculations was involved here, but in a dynamical context which made dubious some of the simplifying assumptions underlying those calculations.

5.30 The first efficiency calculations had been made prior to Los Alamos, at Berkeley, for the case of small excesses over the critical mass. These calculations were preceded by investigation of the hydrodynamical behavior of the core and tamper during the chain reaction, a study which led to the theory of the shock wave which travels into the tamper, and of the rarefaction wave which travels into the core, from the core-tamper interface. The effects of these phenomena on the efficiency were calculated. The diffusion of neutrons was treated by differential theory, which allowed simple estimates of the dependence of efficiency on various tamper properties, such as mean free path, absorption, and density.

5.31 The next step in efficiency calculation - by Group T-4 - was applicable to bombs having a mass far greater than critical. These calculations were based on results obtained by Group T-2, which gave the decrease of the multiplication rate for small expansions of the exploding bomb.

5.32 Once estimates of efficiency in these two cases had been obtained, a semi-empirical formula was developed which fitted the Los Alamos calculations for large excess masses, and reduced in the limit of small excesses to the earlier efficiency formula developed in Berkeley. This formula developed by Bethe and Feynman provided an easy means for making efficiency estimates when the critical mass (or more precisely, the radius to which the core of a given bomb must expand before neutron multiplication is stopped) and the initial multiplication rate were known.

5.33 The possibility of using the Bethe-Feynman formula for intermediate excess masses was justified by the following argument. For small excess masses the effect on the mean density of the ingoing rarefaction and outgoing shock waves approximately canceled. For large excess masses the same thing was true, since in this case the waves would be reflected back and forth many times before the multiplication was stopped, and one could regard the multiplication as a function of the average pressure. A plausibility argument was then invoked to the effect that since this independence of the hydrodynamical details held at both extremes, it also held in the intermediate cases.

5.34 Certain restrictions and unproved assumptions involved in all of the calculations referred to above are listed below:

(a) The effects of radiation can be neglected.
(b) The neutron multiplication can be calculated by an adiabatic approximation.
(c) The tamper and core have the same neutron scattering per unit mass.
(d) The density of material in core and tamper is the same.
(e) The absorption in the tamper is equivalent to that in an infinite nonabsorbing tamper.
(f) The effects of depletion in the material are unimportant.

5.35 Of these six assumptions, (f) was the easiest to allow for. The effects of depletion were negligible for small efficiencies, and could be calculated for larger ones. Rough methods were found for estimating the effect of relaxing (c), (d), and (e). Assumption (b), the error involved in the adiabatic approximation, was investigated in some detail. In this approximation the total number of neutrons in the expanding bomb is assumed to increase at a rate proportional to itself, the rate being calculated for any instant from the excess over critical at that instant, assuming the nuclei of core and tamper to be at rest. This is the same assumption as assumption (b) discussed earlier in connection with diffusion problems. In that case the nuclei are relatively at rest and the assumption is a good one. But during the explosion the bomb material acquires a very high mean mass motion, and the assumption is questionable. A correction factor was found by considering the nonadiabatic theory of small expansions of a slightly supercritical bomb.

5.36 With the exception of assumption (a) as to the effect of radiation, it was possible, by the end of 1943, to give a reasonably good account of the efficiencies to be expected from proposed weapon designs.

5.37 After this time the emphasis in efficiency studies shifted to more specific problems. One was to develop the best possible criteria for the choice of tamper material. A second was to investigate the efficiencies obtainable from implosion bombs. A third was to try to obtain a better understanding of the effects of radiation on the course of the explosion and on the attainable efficiencies.

5.38 The factors affecting the choice of a tamper were investigated in some detail by Group T-3. Apart from radiation (discussed below) the virtues of a tamper could be summarized under two main heads: (1) its neutron reflecting properties, and (2) its effect on the hydrodynamics of the explosion. Point (1) would be understood perfectly by knowing the number of neutrons the tamper scattered back into the core, the time delays involved in this back scattering, and the energy of the neutrons returned. Calculation of these effects depended upon a knowledge of elastic scattering cross sections as a function of the angle of scatter, and of inelastic and absorption cross sections. Point (2) involved calculation of the extent to which various tampers tended by their inertia to hold the active material together during the explosion, and of the behavior of the shock wave in the tamper.

5.39 In connection with its investigation of tamper problems, Group T-3 performed extensive calculations in collaboration with the D-D Group of the Experimental Physics Division, to interpret the scattering data obtained by the latter for various tamper substances. These calculations were limited by the fact that they had to bridge the gap between a detailed theory for which the differential constants were unknown, and a semi-integral type of experiment in which only certain average effects were measured.

5.40 The effects of radiation on the nuclear explosion were, as has been said, the most problematic of the factors that had to be taken into account. A knowledge of the role of radiation was important not only in predicting the efficiency for a given design of weapon, but also in the choice of a tamper. This is so because different tampers have different degrees of transparency to radiation, a property which will affect the course of the explosion and its efficiency. The effect of radiation on the course of the explosion may be described roughly as follows. During the initial expansion of the bomb, the active material is being heated exponentially by the release of fission energy. The tamper is also heated, but far less rapidly. In the time available, the only effective mechanism for the transfer of heat from core to tamper is the outgoing shock-wave.

5.41 Simultaneous with its work on tamper problems and radiation, Group T-3 began, early in 1944, to re-work the earlier calculations of efficiency. The assumption that the multiplication rate depended only on the average pressure over the core and tamper was set aside, and its dependence on the shock and rarefaction waves examined in detail. For this purpose it was first assumed that these were plane waves. Sometime later this assumption was replaced by an "informed guess" as to the effects of convergence and divergence. Only much later were these effects actually calculated. In these calculations it was possible to set aside assumptions (c) and (d), and consider an arbitrary combination of core and tamper materials. Another refinement introduced in these calculations was the replacement of differential diffusion theory by more exact methods.

5.42 In May 1944, while the work described above was under way, the stability considerations brought to the Laboratory by Taylor (5.25) created a new worry about efficiency. When the hot core material pushed against the cold tamper, according to Taylor's principle, the interface would be unstable, and mixing of core and tamper would occur. This might lessen the effectiveness of the tamper. Investigation showed that this effect would probably not be large, since the loss of active material that leaked into the tamper would be partly compensated by the tamper fragments that remained behind. It was observed, moreover, that by the time instabilities could become serious, radiation would have moved the interface between light and dense material some distance out into the tamper, and the mixing that would occur would be mainly of tamper with tamper.

5.43 Another aspect of the efficiency studies of the implosion bomb is that of predetonation. It is true that the initial pressure and density distributions in the implosion are nonuniform, whereas in the gun assembly they are uniform. This difference, however, was shown to be unimportant. The great difference between the two methods lay in the larger neutron background of Pu^{239} and in the dependence of the predetonation probability on the course of the implosion. For a long time, moreover, it was hoped that an efficient weapon would be possible which used only a steady neutron source. In such models the efficiency had to be regarded as a random variable with a rather large dispersion, depending upon the particular moment when a neutron managed to start a divergent chain reaction. This involved the development of the statistical theory of chain reactions in which not only the average number of neutrons per fission played a role, but also the random variation of this number from fission to fission.

The Super

5.44 The deuterium bomb or Super project was relatively divorced from the main work of the Laboratory. As a development secondary to that of the fission bomb, its importance was nevertheless such that it was carried on throughout the course of the Laboratory. From its first conception, before Los Alamos, this work was under the direction of Teller. In the last period of the Laboratory Teller was joined by Fermi. By coincidence the first idea of such a bomb, at least in relation to the Los Alamos program, had been evolved in a lunchtime discussion between Fermi and Teller early in 1942.

5.45 A fundamental understanding of the fast thermonuclear reaction had been reached by the beginning of Los Alamos. In the first rough calculations Teller had ignored the effect of radiation, which is to drain off energy at a rate that increases rapidly with temperature. These early rough calculations indicated that the reaction would take place if ignited by the explosion of a fission bomb as "detonator." They also indicated, in fact, that the reaction would go too well, and that the light elements in the Earth's crust would be ignited.

5.46 The energy transfer phenomenon was well enough understood in the Summer of 1942 to make it apparent that a Super could, in principle, be made. At the Berkeley summer conference in 1942, Teller presented his analysis of the mechanism and argued that such a bomb was feasible. A good part of the discussion at this conference was devoted to the examination of Teller's proposals.

5.47 One further suggestion of great eventual importance was made by Konopinski. This was to lower the ignition temperature of deuterium by the admixture of artificially produced tritium (H^3). The apparently very much greater reactivity of tritium led him to this proposal. It was not immediately followed up because of the obvious difficulty of manufacturing tritium and the hopefulness of igniting pure deuterium. Eventually, as it will develop, new difficulties of ignition were to be uncovered so that the introduction of artificial tritium began to appear necessary.

5.48 One further topic was discussed at the Berkeley conference, the effect of secondary nuclear reactions. Products of the deuterium-deuterium (D-D) reaction were, with about equal probabilities, a He^3 nucleus plus a neutron, or a tritium nucleus and a proton. It was pointed out by Bethe that the reaction of deuterium with tritium, even though secondary, was of considerable importance. The T-D reaction releases nearly five times as much energy as the D-D reaction; the reaction cross section was, moreover, likely to be considerably larger.

5.49 The consequences of the Berkeley discussions of the Super were that its investigation was continued, that measurements of the D-D and T-D cross sections were undertaken, and that, when the Los Alamos Laboratory was being planned, a research program on the Super was included.

5.50 After the conference and before Los Alamos the measurement of the D-D cross section was undertaken by Manley's group at Chicago, and that of the T-D cross section was undertaken by Holloway's group at Purdue.

5.51 At Los Alamos no systematic theoretical work on the Super was undertaken until the Fall of 1943. A Cryogenic Laboratory was started by the group under E. A. Long, with the object of building a deuterium liquefaction plant. A considerable amount of work on the properties of liquid deuterium was carried out by Prof. H. L. Johnston under subcontract at Ohio State University (8.95 to 8.98).

5.52 In September, Teller proposed that there be more intensive investigation of the Super. Experimental cross sections had been revised upward, so that the bomb would be feasible at lower temperatures. In addition there was some slight evidence that the known German interest in deuterium might be directed toward production of a similar bomb. Work was resumed at this time, but not with high intensity. Teller and his group were largely occupied with other and more urgent problems.

5.53 The program of the Super was re-evaluated in February 1944 at a Governing Board meeting. Theoretical difficulties made it appear that it might be difficult to ignite deuterium because of energy dissipation. In case investigations should show that the difficulty of igniting deuterium was too great, there was one remaining alternative, which was to return to the proposal of Konopinski to lower the ignition temperature by admixture of tritium. A small percentage of tritium would bring the ignition temperature down from the neighborhood of twenty kilovolts to around five.

5.54 The practicability of using tritium-deuterium mixtures was limited by the very great difficulty of obtaining tritium. It could be produced from the reaction of neutrons with Li^6, yielding tritium and He^4. The very small sample of tritium that had been used in cross section measurements at Purdue had been produced by cyclotron bombardment. Larger scale production would be possible in such a pile as the Hanford pile, but could utilize only the small percentage of excess neutrons not needed to keep the pile in production.

5.55 Both because of the theoretical problems still to be solved and because of the possibility that the Super would have to be made with tritium, it appeared that the development would require much longer than originally anticipated. Even though this was the case, it was decided that work on the feasibility of so portentous a weapon should be continued in every way possible that did not interfere with the main program. Tolman, who was present at this meeting as General Groves's adviser, affirmed that although the Super might not be needed as a weapon for the war, the Laboratory had a long range obligation to carry on this investigation.

5.56 Although no final decision was made at the meeting referred to, it in fact defined subsequent policy. In Teller's group further theoretical work was carried on, which confirmed the difficulty of igniting pure deuterium.

In May 1944 Dr. Oppenheimer discussed the matter of tritium production with General Groves and C. H. Greenewalt of the du Pont Company. It was there decided that experimental tritium production would be undertaken, using surplus neutrons in the Clinton pile.

Damage

5.57 The detailed investigation of damage and other effects of nuclear explosion was not pursued very far in the period under review. Some results, going beyond the rough estimates reported in paragraph 1.57 were, however, obtained in the summer and fall of 1943. There was further investigation of the shock wave in air produced by the explosion, of the optimum height for the explosion, of the effects of diffraction by obstacles such as buildings, and of refraction caused by temperature variation. There was some calculation of the energy that might be lost through the evaporation of fog particles in the air. Estimates were made of the size of the "ball of fire" after the explosion, and the time of its ascent into the stratosphere. The theory of shallow and deep underwater explosions was investigated, and led to the suggestion of model experiments.

5.58 One important question was cleared up at this time, which was the nature of the dependence of damage upon the characteristics of a shock wave in air. For small explosions damage is roughly proportional to the impulse, which is pressure-integrated over the duration of the pulse (i.e., the average pressure of the pulse times its duration). Investigation made clear the fact (not unknown elsewhere) that existing blockbusters are near the limit of size at which further increase of the duration of the pulse has any advantageous effect on the damage. For large explosions such as those contemplated, damage depended only on the peak pressure. This was important because the peak pressure depended on the cube root of the energy, whereas the impulse depended on its two-thirds power. Large bombs are relatively less effective (from the point of view of purely physical damage) than small ones for this reason. Calculations made at the time showed that for bombs of the order of 10,000 tons of TNT, the peak pressure would fall below the level of "C" damage at a radius of 3.5 kilometers.

5.59 Another important point was clarified at this time, connected with the optimum height of detonation. It had been known that the reflection of shock waves by solid obstacles increases the pressure of the shock wave. It was shown at this time, however, that this effect was much greater for oblique incidence than had been believed from elementary considerations; in fact oblique incidence up to an angle of 60 or 70° from the vertical gives a greater pressure increase than normal incidence. Hence it was concluded that a considerable improvement in the damage radius could be obtained by detonation at an altitude not small compared to the expected radius of damage - in fact of 1 or 2 kilometers.

Experiments

5.60 Some of the more important cooperative work between the Theoretical Division and the other divisions of the Laboratory has already been mentioned; for example, the interpretations of scattering data, and calculations of the water boiler and hydride critical masses, and the calculations made of the hydrodynamical characteristics of the implosion. There was, however, a more extensive cooperation than these isolated instances would suggest. Work done ranged from cases such as these in which the theorists played a large and semi-independent role, to ordinary service calculations, particularly the analysis of experimental data. For this latter work and for consultation in the design of experiments, every experimental group had theorists assigned to it. Calculations of a fairly extensive sort were necessary in all experiments in which "integral" considerations were involved, i.e., in which the results depended upon nuclear constants in a complex statistical way. For it then became necessary to relate the measured quantities with these constants by theory, and first to use this theory to decide whether a given experimental design would yield sufficient accuracy to justify its execution, and second to interpret the data obtained. The theorists played this part in most of the experimental determinations of nuclear quantities described in Chapters VI and XII.

5.61 One rather conspicuous example of theoretical influence on the design of experiments was the "Feynman experiment," an experiment which was never performed but whose principle was embodied in several experiments. This was simply the proposal to assemble near-critical or even supercritical amounts of material safely by putting a strong neutron absorber (the B^{10} boron isotope) uniformly into the core and tamper. For an absorber with an absorption cross section inversely proportional to the velocity of the neutrons absorbed, it could be shown that the effect was to decrease the multiplication rate in the system by an amount which was directly proportional to the concentration of absorber. Thus an amount of material which would be supercritical could be made subcritical by the addition of boron; from a measurement of the rate at which the neutron died out in this system, the rate could be simply calculated at which they would increase if the boron were absent.

5.62 The theoretical groups assisted the Detector Group of the Experimental Physics Division and others in the theoretical analysis of the efficiency and other characteristics of detectors and counters.

5.63 Aside from its main work in connection with the gun and implosion assemblies, discussed above, the Theoretical Division made numerous other analyses and calculations relative to the experimental work of the Ordnance Division. In preparation for the RaLa experiments for example, Group T-3 analyzed the attenuation of gamma rays in a homogeneous metal sphere surrounding the source, and calculated the way in which this attenuation would be increased with compression during the course of an implosion of the metal sphere. As another example, the theory of the magnetic method of implosion study was investigated in the Theoretical Division in collaboration with the experimentalists.

5.64 Mention should be made here of safety calculations made by Group T-1 and later by Group F-1 for the Y-12 and K-25 plants. The Group Leader, E. Teller, was appointed as consultant for the Manhattan District as a whole on the dangers of possible supercritical amounts of material being collected together in the plants producing separated U^{235}.

5.65 During the period described the computations group, T-5, carried out innumerable calculations for other groups in the division, and for related investigations in the mathematical theory of computation. Like other service groups, its scanty mention is no indication of the importance of its work, without which the work of the division would have been, in fact, impossible.

radical implosion design tested at Trinity. During the earlier period of the Laboratory the possibility of a U^{235} implosion bomb had not been ruled out. With the acquisition of accurate means of calculation and reliable cross section data, it became evident that such an implosion would be considerably less efficient than the plutonium implosion. This fact, added to the uncertainties of the whole implosion program, made it seem desirable to plan for the use of U^{235} by the gun method alone. Toward the end of the war the possibility of composite (U^{235} + Pu^{239}) implosion bombs was considered (11.2, 20.2). By the time of the "freeze" of the Laboratory program in February 1945 (11.10), the decision was final to use U^{235} only in the gun model.

10.3 This quiet and efficient group continued at the center of an affiliated program in the Research Division, the Theoretical Division, other groups of the Ordnance Division, and in the Alberta Project (Ch. XIX). From the Research Division, Group T-2 was able to obtain information on the nuclear properties of U^{235} sufficient to provide accurate data for critical mass calculations and calculation of the amount of material that could be safely used. From the sphere multiplication experiments of R Division, a still more accurate calculation of the critical mass could be obtained, by extrapolation. The gun was "mocked" by the model experiment in the same division, and this provided an integral check of the calculations of the performance of the weapon, including predetonation probability. The finished projectile and target, finally, were brought to the critical point by the Critical Assemblies Group of G Division shortly before shipment to Tinian for combat use. This assembly was a final check of the accuracy of predictions as to the point at which the system would become supercritical. Reliable efficiency calculation was made possible by theoretical and experimental estimation of the initial multiplication rate of the fully assembled bomb.

10.4 The fabrication of the projectile and target was the responsibility of members of Groups CM-2, -7, and -11 of the Chemistry and Metallurgy Division. Fabrication included the forming of the active material into pieces of proper shape and purity, and the steel casing that housed the target. The final design of the outer case, originally the responsibility of the Engineering Group of the Ordnance Division, was almost entirely transferred to the Gun Group during this period. Responsibility for the fusing and detonating system remained with the Fuse Group of the Ordnance Division. The Gun Group and the Fuse Group collaborated in the drop tests of the Little Boy carried out as part of the program of Project Alberta.

The Plutonium Bomb

10.5 At the beginning of the period under discussion, the hope for a successful implosion was so low that F Division was given the responsibility soon after its creation, of investigating even the slim possibility that as an alternative, an autocatalytic system of assembly utilizing plutonium might be found meritorious. The desirability of such systems was not immediately evident and in the meantime the Weapon Physics Division, the Explosives Division, and the Theoretical Division were preparing themselves for a direct attack on the implosion problem.

10.6 Prediction based on the analysis of Clinton plutonium led to the expectation that the Hanford plutonium would produce a large number of neutrons per second, in bomb-amounts of plutonium, from the spontaneous fission of Pu^{240} alone. Light impurities would produce additional neutrons, but purification would keep this contribution small compared to that from spontaneous fission. Only the implosion would be fast enough to assemble the plutonium in a time short enough to avoid predetonation.

10.7 The "direct attack" on the implosion problem included the continuation of small scale implosion studies in the new X Division, with particular emphasis on interpreting the causes of jets and irregularities, including the careful investigation of the source of timing errors in multipoint detonation and their contribution to asymmetries. The first lens test shot was fired in November 1944. In the meantime G Division was getting under way its many-sided effort to examine the implosion experimentally, was beginning work on electric detonators, and was planning the hydride critical experiments as a step to eventual critical assemblies of active metal. At the same time the Theoretical Division was completing its studies of the "ideal" implosion (which began with a spherically converging shock-wave), and was turning its attention to the theoretical interpretation of the jets and asymmetries that had been found in less-than-ideal experimental implosions.

10.8 In the Explosives Division means for preventing the development of irregularities were under investigation. Early results from the lens program in X Division, meanwhile, showed that a converging spherical detonation wave could be approximated by a lens system, provided a sufficient degree of simultaneity could be obtained for all lenses. Thus although there was as yet no sure path to success, hopeful directions of development had been marked out.

10.9 At the end of February 1945, a conference was held at Los Alamos, with General Groves present, at which it was decided that the time

Chapter XI

THE THEORETICAL DIVISION

Introduction

11.1 During the second period, from August 1944 to August 1945, the Theoretical Division took part in the general expansion of the Laboratory to the extent of increasing the size of its groups and adding three new groups. In comparison with other divisions it had relatively little administrative history. It was not seriously involved with the general Laboratory problems of personnel, construction, transportation, nor was it involved except in an advisory way with the complicated procurement and scheduling operations of the Trinity test and Project Alberta. It was therefore able to administer itself and do its work rather unobtrusively. Nevertheless it was an essential part of the final development program. As it gathered power from its earlier work, it was able to handle more realistic and complex problems with increasing efficiency, and to gain increased understanding of the difficult hydrodynamical questions involved in the implosion and the nuclear explosion, to refine its earlier calculations concerning critical masses and efficiencies, and to provide reliable interpretation of many integral experiments.

11.2 The Group Structure of the division by August 1945 was as follows:

T-1	Implosion Dynamics	R. E. Peierls
T-2	Diffusion Theory	Robert Serber
T-3	Efficiency Theory	V. F. Weisskopf
T-4	Diffusion Problems	R. P. Feynman
T-5	Computations	D. A. Flanders
T-6	IBM Computations	E. Nelson
T-7	Damage	J. O. Hirschfelder
T-8	Composite Weapon	G. Placzek

11.3 Group T-6 was added in September 1944 to operate the IBM machines, under S. Frankel and E. Nelson. Frankel left this group in January 1945 to join the Theoretical Group of F Division. Group T-7 was formed in November 1944 by a change of name. It was the former O-5 Group, already for practical purposes a part of the Theoretical Division. At the time of this formal change of status, however, the group was given the responsibility for completing earlier investigations of damage and of the general phenomenology of a nuclear explosion. Group T-8 was added in May 1945 upon the arrival from Montreal of G. Placzek. The responsibility of this group was to investigate future fission bomb possibilities, specifically the composite core implosion, intended to use U^{235} (with Pu^{239}) more efficiently than would be possible by gun assembly.

Diffusion Problems

11.4 Although by August 1944 the essential difficulties of the one-velocity diffusion problem had been overcome, even the most economical method (expansion of the neutron distribution in spherical harmonics) was still rather expensive. A very great simplification of these calculations was accomplished by Group T-2 in the fall of 1944, when an analytical expression was developed which by comparison with previously computed critical radii gave accuracies within 1 to 2%. This method made use of simple solutions for the shape of the neutron distribution far from boundaries (such as the boundary between core and tamper), and then fitted these solutions discontinuously at the boundary in such a way that the critical radius was given. From this time on, solutions for a great variety of critical radius or mass problems were proliferated extensively, and even reduced to nomographic form, permitting very rapid calculation.

11.5 Throughout the period under review various groups in the Theoretical Division, but particularly T-2, were concerned with special problems arising out of sphere multiplication experiments carried out in R Division. These calculations had to take into account the variation of the average cross sections after the initial and each following collision of neutrons emerging from a central source. The number of neutrons coming out of the sphere as a function of the number of source neutrons was calculated for various size spheres and for various dispositions of the source. These calculations agreed very closely with the measured values; and as larger spheres of U^{235} became available, it was possible to extrapolate to the critical mass with very high accuracy (12.18-12.23).

Chapter XIII

F DIVISION

Introduction

13.1 As part of the administrative reorganization of the Laboratory, F Division was formed in September 1944, shortly after Fermi's arrival from Chicago. As Associate Director, Fermi was given general responsibility for the theoretical and nuclear physics research of the Laboratory. As Division Leader of F Division he was given the directive to investigate potentially fruitful lines of development not included under the main program of the Laboratory. This responsibility included the Super in its theoretical and experimental aspects and means of fission bomb assembly alternative to the gun and the implosion. Because of Fermi's previous association with pile development, the Water Boiler Group was also placed in this division. The last group in the division was added in February 1945 to do experimental work with the high power Water Boiler as a neutron source, and to prepare for the measurement of fission fragments at the Trinity test. The work of F Division in the Trinity test is reported in Chapter XVIII.

13.2 The group organization was as follows:

F-1	The Super and General Theory	E. Teller
F-2	The Water Boiler	L. D. P. King
F-3	Super Experimentation	E. Bretscher
F-4	Fission Studies	H. L. Anderson

The Super

13.3 During June 1944 Teller's group had been separated from the Theoretical Physics Division and placed in an independent position, reporting to the Director. This separation was a recognition of the exploratory character of this group's work as contrasted with that of the Theoretical Division generally, which had, primarily, responsibility for obtaining design data for fission bombs. Again in September 1944 Teller's group became the theoretical branch of the new F Division, created under Fermi.

13.4 Theoretical work on the Super from this time was without essential surprises. The analysis of the thermonuclear reaction became more quantitative and concrete. Increasing attention was given to the theory of detonation mechanisms. Work reached its highest intensity in the spring of 1945 and continued for several months after the end of the war and the period covered by this report.

13.5 Various models were investigated. The end sought was a bomb burning about a cubic meter of liquid deuterium. For such a bomb the energy-release will be about ten million tons of TNT.

DAMAGE

13.6 No account of the Super development at Los Alamos can be complete without some account of estimates of damage. It must be emphasized that these considerations are essentially qualitative. In fact with energies of the order contemplated, the effects of explosions begin to enter a new range, which may make necessary some account of meteorological and geological phenomena normally beyond human control. Under these circumstances accurate calculation is less important than a thorough canvassing of the possibilities. The following account is highly tentative, both quantitatively and in degree of thoroughness.

13.7 The ten million ton Super described above would not be the largest explosion seen on the Earth. Volcanic explosions and the collision of large meteorites such as the Arizona or Siberian have undoubtedly produced larger blast energies, perhaps a thousand or ten thousand times larger. On the other hand these explosions were very cool compared to a thermonuclear explosion, and correspondingly more familiar in their effects.

13.8 The blast effects from a ten million ton Super can be scaled up from the known damage at Hiroshima and Nagasaki. Taking the destroyed area from a ten thousand ton bomb to be ten square miles, the Super should produce equal blast destruction over a thousand square mile area. This would be more than enough to saturate the largest metropolitan areas.

13.9 More widespread ground damage would perhaps result from an explosion underground or underwater near a continental shelf. Since it is estimated that a severe earthquake produces energies of the same order as the Super, the surface effects might be comparable. To produce these effects would require ignition at a very great depth, of the order of several miles.

13.10 This bomb begins to reach the upper limit for blast destruction that is possible from detonation in air. Just as a fission bomb exploded in shallow water will have its radius of destruction in water limited by the depth at which it is exploded (14.18), so with a Super in the atmosphere. It "blows a hole" in the atmosphere, so that the maximum radius of destruction is comparable to the depth of the atmosphere.

13.11 Neutrons and gamma rays from the Super would not be a significant part of its damage; their intensity falls off more rapidly with distance than the blast effects. Even at Hiroshima and Nagasaki they did not cause a large percentage of casualties. From a larger bomb their effects would be greater, but not proportionately greater.

13.12 The effects of visible radiation, on the other hand, fall off less rapidly than blast effects. This destruction can, in fact, be made directly proportional to the energy release. While blast damage can be increased a hundredfold, visible radiation damage can be increased a thousandfold. For the first purpose the bomb would be detonated about ten times higher than at Hiroshima and Nagasaki, for the second about thirty times higher. And the real point of the latter method is that there is no limit to the possibility of detonating larger bombs at higher altitudes. Thus a Super which burned a ten-meter cube of deuterium at a height of three hundred miles would equal in effect a thousand "ordinary" Supers detonated at ten-mile altitudes. In both cases the area of damage would be in the neighborhood of a million square miles. It should, of course, be emphasized that such a high altitude weapon is at the present time only a theoretical possibility.

13.13 It is difficult to estimate damage from visible radiation. In Hiroshima and Nagasaki the total effect was a composite of blast, gamma radiation, and visible radiation. The last was sufficiently intense to ignite wooden structures over an area of a square mile or so. Casualties from visible radiation alone would be considerably smaller, because of the protecting effect of clothing and walls. Effects from a Super would be comparable, and either more or less intense depending on the relative military importance of extensive versus intensive burning. The figures already given would correspond to an intensity about the same as that at Hiroshima and Nagasaki.

13.14 The most world-wide destruction could come from radioactive poisons. It has been estimated that the detonation of 10,000 to 100,000 fission bombs would bring the radioactive content of the Earth's atmosphere to a dangerously high level. If a Super were designed containing a large amount of U^{238} to catch its neutrons and add fission energy to that of the thermonuclear reaction, it would require only in the neighborhood of 10 to 100 Supers of this type to produce an equivalent atmospheric radioactivity. Presumably Supers of this type would not be used in warfare for just this reason. Without the uranium, poisonous radioactive elements could be produced only by absorption; for example C^{14} could be produced in the atmosphere; not, however, in dangerous amounts. Poisoning, moreover, would be obviated by detonation above the atmosphere, which is in any case the region in which the general destructive effects of the Super seem greatest.

Other Theoretical Topics

13.15 The gloomy prospects of the implosion in the fall and winter of 1944-45 made it desirable again to investigate autocatalytic and other possible methods of weapon assembly. This whole subject, which had been investigated earlier, had been given up because of the uniformly low efficiencies indicated. The operating mechanism of autocatalysis makes use of neutron absorbers which are removed in the course of the initial explosion. Thus, for example, one or more paraffin spheres coated with B^{10} may be placed inside the fissionable material, in such a way that the whole assembly is just subcritical. If by some means a chain reaction is started, the heating of the material will result in the compression of the boron "bubbles," the reduction of the neutron absorbing area, and a consequent increase in the degree of criticality. Thus in principle the progress of the explosion creates conditions favorable to its further progress. Unfortunately, the autocatalytic effect is not large enough to compensate for the poor initial conditions of this type of explosion, and the result is not impressive.

13.16 Another type of assembly mechanism examined was one that made use of shaped charges to attain much higher velocities for a slug of active material than would be possible with conventional gun mechanisms. This method also gave low efficiency when calculated for the high neutron background of Hanford plutonium.

13.17 Another topic of continuing interest was the possibility of various types of controlled or partially controlled nuclear explosions, which would bridge the gap between such experiments as the "dragon" (15.7) and the final weapon.

13.18 Some time was spent on safety calculations for the K-25 diffusion plant, principally on estimations of critical assemblies of enriched uranium hexafluoride under various conditions and degrees of enrichment.

13.19 A topic of interest in connection with the Trinity test was the formation of chemical compounds in air by the nuclear explosion. Such compounds as oxides of nitrogen and ozone are poisonous, and the quantity produced had to be estimated. It was also anticipated that they would effect the radiation history of the explosion, which was to be examined spectrographically.

Deuterium and Tritium Reaction Cross Sections

13.20 The low energy cross section of the T-D reaction was found to be higher than extrapolation from high energy data had indicated. This discovery, which considerably lowered the ignition temperature of T-D mixtures, was the result of work undertaken at the beginning of the period under review by Group F-3, the Super Experimentation Group.

13.21 Since both the T-D and the D-D cross sections at low energies were known only by rather dubious extrapolation, it was planned to measure them simultaneously.

13.22 The first series of measurements was made with a small (50 kev) Cockcroft-Walton accelerator constructed for the purpose at Los Alamos. With this equipment experiments were carried out in the region from 15 to 50 kev. The quantity measured was the total number of disintegrations as a function of the bombarding energy, from which the reaction cross sections could be derived. In both cases the target used was made of heavy ice cooled with liquid nitrogen. The D-D reaction was produced by a deuterium ion beam, and the protons produced in the reaction measured. In the case of the T-D reaction the procedure was analogous, except that special precautions had to be taken to conserve the small amount of tritium available as an ion source. In this case the alpha particles from the reaction were counted.

13.23 The result of these measurements was that the extrapolated values of the D-D cross section were shown to be approximately correct. The tritium cross section, however, was very much larger than had been anticipated at energies of interest.

13.24 These measurements were later (after the end of the period under review) extended to the 100 kev region, using a larger accelerator constructed for the purpose.

The Water Boiler

13.25 Upon the completion of the series of Water Boiler experiments described in Chapter VI, it was decided to develop a higher power boiler to be used as a strong neutron source for various experiments. A power of 5 kilowatts was chosen as a suitable value. The original 10 kilowatt design was modified considerably. The essential design features were completed in October and construction of concrete foundations and shields begun. The boiler was built and in operation in December 1944.

13.26 The power level for which the boiler was designed was chosen because this was attainable with the amount of enriched material available at the time, because the cooling requirements would be simple, and because the chance of trouble from frothing or large gas evolution caused by electrolysis of the solution would be small. Such a boiler was calculated to give a flux of 5×10^{10} neutrons per square centimeter per second.

13.27 A number of changes in design were made from that of the low power boiler, and some from the original 10 kilowatt design. The solution used was uranyl nitrate rather than uranyl sulfate. The main reason for this was the greater ease with which the nitrate could be decontaminated if that should prove necessary (17.37). Additional control rods were installed for increased flexibility of operation. Water cooling and air flushing systems were installed, the latter as a means for removing gaseous fission products. The boiler had, finally, to be carefully shielded because of gamma radiation and neutrons.

13.28 It turned out that decontamination of the boiler was unnecessary, even after 2500 kilowatt-hours of operation. This was caused in part by the success of the air flushing system, which removed some 30% of the fission products, and in part by the absence of corrosion of the stainless steel container.

13.29 The tamper of the high power boiler was chosen on the basis of tamper experiments performed with the low power boiler before it was torn down. Partly because of the difficulty of procuring the needed amount of beryllia, and partly because of the (γ, n) reaction in beryllium which it was desirable to avoid, the tamper chosen was only a core of beryllia bricks, surrounded by a layer of graphite.

13.30 The power boiler was equipped with a graphite block for thermalizing fission neutrons.

Neutron Physics Experiments

13.31 It has been mentioned in Chapter XII (12.23) that the important sphere multiplication experiments which were made first in the Electrostatic Generator Group were repeated and verified in F Division. These experiments were performed independently by the Water Boiler Group and the F-4 Group. In both experiments a source of fission neutrons was obtained by feeding a beam of thermal neutrons from the Water Boiler and graphite block on to a target of U^{235} in the center of the $3\frac{1}{2}$" and $4\frac{1}{2}$" U^{235} spheres. In the Water Boiler Group the fissions in the source and throughout the sphere were measured by a technique similar to that used by the Electrostatic Generator Group, catching the fission fragments on cellophane foils. In the experiments of F-4 the fissions produced were measured by means of a small fission chamber placed at various radial distances from the center. In these experiments the U^{235} target was itself a small fission chamber identical with that used to measure fissions in the sphere. Comparison of fissions in the source chamber with those in the detecting chamber at various distances gave the multiplication rate. Of these two experiments the first gave results closer to those of the Electrostatic Generator Group, and to the final empirically established values of the critical mass.

13.32 Several thermal cross section measurements for the various elements were made, using the high neutron flux from the boiler. One was the absorption cross section of U^{233}. The thermal scattering cross sections of U^{235} and Pu^{239} were measured, and in the course of these measurements cross sections were also obtained for a large number of other elements.

13.33 In order to make calibrations for the measurement of gamma ray and neutron intensities at the Trinity test, the Water Boiler Group made measurements of delayed neutron and gamma ray emission from samples of Pu^{239}, as a function of the delay time (i.e., the time after irradiation). These experiments made use of a rather spectacular technique, which was to shoot a slug of material with a pneumatic gun into a pipe through the middle of the boiler, and measure the decay of activity with time by means of an ionization chamber for gamma rays and a boron trifluoride counter for neutrons.

13.34 In addition to providing a strong neutron source for the experiments described above, the Water Boiler also was used to make neutron irradiations for other groups in the Laboratory.

WET PURIFICATION

17.18 Shortly after the beginning of this period the first completely enclosed full scale apparatus was completed. The full run of 160 grams required 24 hours, with about 60 liters of supernatant remaining for recovery. Aside from minor difficulties and improvements, this represented the completed form of the "A" process of wet purification, described in Chapter VIII (8.30).

17.19 Early in 1945 investigation and testing of a "B" and "C" wet process began. The "B" process, the one finally adopted for routine plutonium purification, was simpler than the "A" process, and gave higher yields and a smaller volume of supernatants. It involved only two steps: an ether extraction with calcium nitrate, and an oxalate precipitation. The process met purity requirements and gave a product satisfactory for further processing. In July 1945 the "A" process was dropped completely.

17.20 For a time some thought was given to an even simpler "C" process involving only an oxalate precipitation. Purification, however, was not sufficient. The chart on the following page gives the essential information on the "A" and "B" processes.

DRY CONVERSION

17.21 After it was decided to employ only fluoride metal reduction (8.43), effort was concentrated on the production of the fluoride. Three methods were investigated, involving nitrate, oxalate, and oxide hydrofluorination. The method finally chosen was the oxide method, which involved the conversion of the oxalate from wet purification to oxide by heating in oxygen, and introducing hydrogen fluoride at 325°C in the presence of oxygen. The process involved a 24 hour cycle, and gave yields of 92 to 99%.

RECOVERY

17.22 Aside from recovery methods developed earlier (8.34 ff), the principal development of this period was that of peroxide precipitation. Of the four steps first employed--oxalate precipitation, ether extraction, sodium plutonyl acetate precipitation, and a final oxalate precipitation--the ether step was eliminated, and the sodium plutonyl acetate step used only for rather heavily contaminated material.

17.23 The danger of plutonium to the health of operators was greatest

"A" Process

Nitrates from X or W

↓ reduction with dilute HNO_3 and HI

Pu^{+++}

↓ $H_2C_2O_4$

$Pu_2(C_2O_4)_3$, $9H_2O$

↓ oxidation with $NaBrO_3$ and HNO_3

PuO_2^{++}

↓

$NaPuO_2Ac_3$

↓ HNO_3

PuO_2^{++}

↓ ether extraction with NH_4NO_3 and HNO_3

PuO_2^{++}

↓ reduction with dilute HNO_3 and HI

Pu^{+++}

↓

$Pu_2(C_2O_4)_3$, $9H_2O$

Yield 95 per cent
supernatant 60 liters
16 - 24 hours run

"B" Process

Nitrates from X or W

↓ oxidation

PuO_2^{++}

↓ ether extraction $Ca(NO_3)_2$ and HNO_3

PuO_2^{++}

↓ reduction with dilute HNO_3 and HI

Pu^{+++}

↓ $H_2C_2O_4$

$Pu_2(C_2O_4)_3$, $9H_2O$

Yield near 100 per cent
supernatants 30 - 40 liters
10 - 11 hours run

of 3 Mev at 200 meters.

(c) The conversion of plutonium to fission products, measured by determining the ratio of fission products to Pu, gave a result equivalent to 18,600 tons of TNT. An attempt to collect fission products and plutonium on filters from planes at high altitude from the dust of the shot after it circled the world gave no results, although later some indications were obtained after the Hiroshima explosion by this method.

Damage, blast and shock experiments were divided into three groups: (a) blast, (b) earth shock, and (c) ignition of structural materials.

(a) Blast measurements included:

(1) Quartz piezo gauges - these gave no records since the traces were thrown off scale by radiation effects.
(2) Condenser gauges of the California Institute of Technology type were dropped from B-29 planes but no records were obtained because the shot had to be fired when the planes were out of position.
(3) The excess velocity of the shock wave in relation to sound velocity was measured with a moving coil loudspeaker pick-up, by the optical method with blast-operated switches and torpex flash bombs, and by the Schlieren method. By the moving coil loudspeaker method the velocity of sound was obtained for a small charge and then the excess velocity for the bomb; this measurement gave a yield of 10,000 tons and proved to be one of the most successful blast measuring methods.
(4) Peak pressure measurements were done with spring-loaded piston gauges at an intermediate pressure range of from 2.5 pounds to 10 pounds per square inch, with the same kind of gauges above ground and in slit trenches at a pressure range of from 20 to 150 pounds per square inch, with crusher type gauges, and with aluminum diaphragm "box" gauges at a range of from 1 to 6 pounds. The first of these methods gave blast pressure values which were low compared to all other methods, the crusher type gauges gave the highest pressure range, and the box gauges gave a TNT equivalent to 9900 ± 1000 tons. This last method was found to be inexpensive and reliable.
(5) Remote pressure barograph recorders gave results consistent with 10,000 tons. These were necessary for legal reasons.
(6) Impulse gauges - mechanically recording piston liquid and

orifice gauges - also gave results consistent with 10,000 tons.

(7) Mass velocity measurements were made by viewing with Fastax cameras suspended primacord and magnesium flash powder.

(8) Shock wave expansion measurements were made with Fastax cameras at 800 yard stations and gave a total yield of 19,000 tons.

(b) Earth shock measurements included:

(1) Geophone measurements with velocity-type moving coil strong motion geophones gave 7000 tons after extrapolation from a small charge and 100 ton data.

(2) Seismograph measurements done with Leet 3-component strong motion displacement seismographs gave results of approximately 15,000 tons. These were necessary for legal reasons.

(3) Permanent earth displacement measurements using steel stakes for level and vertical displacements gave results of 10,000 ± 5000 tons.

(4) Remote seismographic observations at Tucson, El Paso, and Denver showed no effect at these distances.

(c) The ignition of structural materials was observed using roofing materials, wood, and excelsior on stakes. Observations showed that the risk of fire produced by radiant energy is small for distances greater than 3200 feet. The risk of fire from direct radiation was likely to be much less than the risk of fire from stoves, etc., at the time of the explosion. These conclusions were confirmed at Hiroshima and Nagasaki.

The study of general phenomena consisted chiefly of photographic studies of the ball of fire and the column of blast cloud effects. This group of studies did include a radar study with 2 SCR-584 radars in which two plots of the cloud were obtained; radar reflection, however, was not found to be favorable. Photographic equipment used for these studies included Fastax cameras ranging from 800 to 8000 frames per second, standard 16 millimeter color cameras, a 24 frame per second Cine-Special, 100 frames per second Mitchell cameras, pinhole cameras, gamma ray cameras, Fairchild 9 x 9 inch aero view cameras at 10,000 yards and at 20 miles for stereo-photos. These photographic records were extremely valuable.

The rise of the column was followed with searchlight equipment and the first 18 miles of the main cloud path was obtained by triangulation. A part of this group of experiments was a number of spectrographic and photometric measurements and measurement of total radiation. Spectrographic measurements were done with Hilger and Bausch and Lomb high-time-resolution spectrographs, photometric measurements with moving film and filters and with photocells and filters recording on drum oscillographs, and total radiation measurements with thermocouples and recording equipment.

Post-shot radiation measurements included:

(a) Gamma-ray sentinels - these ionization chambers which recorded at 10,000 yard shelters were extremely valuable in giving the distribution of radioactive products immediately after the shot until safe stable conditions were assured.
(b) Portable chamber observations in the high gamma flux region were made from heavily shielded army tanks using portable ionization chambers of standard design about 4 hours after the shot, and ionization data from these chambers were radioed back to the control shelter.
(c) A dust-borne product survey was made by the Health Group with portable alpha and gamma ionization chambers and Geiger counters, both at the site of the explosion and at remote points up to 200 miles in order to measure dust-deposited fission products.
(d) Measurement of airborne products from B-29 planes equipped with special air filters was unsuccessful as noted above under blast measurements (2).
(e) A detailed crater survey was made with ionization chambers and amplifiers after 4 weeks and showed approximately 15 roentgens per hour at the edge of the crater and 0.02 roentgen per hour at 500 yards.

Weather information was obtained up to 45 minutes before the shot from the point of detonation to 20,000 feet and 25 minutes after the shot. Low level smoke studies were made to determine the spread of active material in case the nuclear explosion failed to occur. This information was vitally important for the success of the test.

tests on August 8 was conducted as a final rehearsal for delivery and used a unit that was complete except for active material.

19.15 The U^{235} projectile for the Little Boy was delivered at Tinian by the cruiser Indianapolis on July 26, only a few days before its tragic sinking off Peleliu. The Indianapolis had been especially held at San Francisco to wait for this cargo, and had then made a record run across the Pacific. The rest of the U^{235} components arrived on the 28th and 29th of July, as the only cargo of three Air Transport Command C-54's. Since the earliest date previously discussed for combat delivery was August 5 (at one time the official date was August 15). Parsons and Ramsey cabled Gen. Groves for permission to drop the first active unit as early as August 1. Although the active unit was completely ready, the weather was not, and the first four days of August were spent in impatient waiting. Finally on the morning of August 5 a report came that weather would be good the following day, and shortly afterwards official confirmation came from Maj. Gen. LeMay, Commanding General of the 20th Air Force, that the mission would take place on August 6. The Little Boy was loaded onto its transporting trailer the moment the official confirmation came through and was taken to the loading pit and loaded into the B-29. Final testing of the unit was completed and all was ready early in the evening. Between then and takeoff the aircraft was under continuous watch both from a military guard and from representatives of the key technical groups. Final briefing was at midnight, and shortly afterward the crews assembled at their aircraft under brilliant floodlights with swarms of photographers taking still and motion pictures. For this mission Col. P. W. Tibbets was pilot of the Enola Gay, the B-29 which carried the bomb. Maj. Thomas Ferebee was bombardier, Capt. Parsons was bomb commander, and Lt. Morris Jepson was electronics test officer for the bomb.

19.16 Only a few days before the scheduled drop it was decided by the technical group that it was not safe to take off with the bomb completely assembled, since a crash might mean tremendous destruction to men and materials on Tinian. Full safing could not be secured, but it was finally agreed that a partial safeguard would come if the cartridge which contained the propellant charge were inserted through the opening in the breech block during flight rather than on the ground. This scheme had been considered before (14.14) but was not finally adopted until this time. Capt. Parsons, who was already assigned to the crew as weaponeer, was given the job. This decision meant that Capt. Parsons had to be trained in a short time to perform the operation, and also that the bomb bay of the B-29 had to be modified to provide him with a convenient place to stand while completing the assembly. These things were done and the bomb was not completely assembled until the plane was safely in the air.

19.17 The progress of the mission is described in the log which Capt. Parsons kept during the flight:

6 August 1945

0245 Take Off
0300 Started final loading of gun
0315 Finished loading
0605 Headed for Empire from Iwo
0730 Red plugs in (these plugs armed the bomb so it would detonate if released)
0741 Started climb

Weather report received that weather over primary and tertiary targets was good but not over secondary target

0838 Leveled off at 32,700 feet
0847 All Archies (electronic fuses) tested to be OK
0904 Course west
0909 Target (Hiroshima) in sight
0915-1/2 Dropped bomb (Originally scheduled time was 0915)

Flash followed by two slaps on plane. Huge cloud

1000 Still in sight of cloud which must be over 40,000 feet high
1003 Fighter reported
1041 Lost sight of cloud 363 miles from Hiroshima with the aircraft being 26,000 feet high

The crews of the strike and observation aircraft reported that 5 minutes after release a low 3 mile diameter dark grey cloud hung over the center of Hiroshima, out of the center of this a white column of smoke rose to a height of 35,000 feet with the top of the cloud being considerably enlarged. Four hours after the strike, photo-reconnaissance planes found that most of the city of Hiroshima was still obscured by the cloud created by the explosion, although fires could be seen around the edges. Pictures were obtained the following day and showed 60 per cent of the city destroyed.

19.18 The active component of the Fat Man came by special C-54 transport. The HE components of two Fat Men arrived in two B-29's attached to the 509th Group, which had been retained at Albuquerque especially for this purpose. In all cases the active components were accompanied by special personnel to guard against accident and loss.

19.19 The first Fat Man was scheduled for dropping on August 11 (at one time the schedule called for August 20, but by August 7 it was apparent that the schedule could be advanced to August 10. When Parsons and Ramsey proposed this change to Tibbets he expressed regret that the schedule could not be advanced two days instead of only one, since good weather was forecast for August 9 and bad weather for the five succeeding days. It was finally agreed that Project Alberta would try to be ready for August 9, provided it was understood by all concerned that the advancement of the date by two full days introduced a large measure of uncertainty. All went well with the assembly, however, and the unit was loaded and fully checked late in the evening of August 8. The strike plane and two observing planes took off shortly before dawn on August 9. Maj. C. W. Sweeney was pilot of the strike ship Great Artiste, Capt. K. K. Beahan was bombardier, Comdr. Ashworth was bomb commander, and Lt. Philip Barnes was electronics test officer.

19.20 It was not possible to "safe" the Fat Man by leaving the assembly incomplete during takeoff in the same manner as the Little Boy. The technical staff realized that a crash during takeoff would mean a serious risk of contaminating a wide area on Tinian with plutonium scattered by an explosion of the HE, and even some risk of a high-order nuclear explosion which would do heavy damage to the island. These risks were pointed out to the military with the request that special guarding and evacuation precautions be taken during the takeoff. The Air Force officer in command decided that such special precautions were not necessary, and as it turned out the takeoff was made without incident. This mission was as eventful as the Hiroshima mission was operationally routine. Comdr. Ashworth's log for the trip is as follows:

0347 Take off
0400 Changed green plugs to red prior to pressurizing
0500 Charged detonator condensers to test leakage. Satisfactory.
0900 Arrived rendezvous point at Yakashima and circled awaiting accompanying aircraft.
0920 One B-29 sighted and joined in formation.
0950 Departed from Yakashima proceeding to primary target Kokura having failed to rendezvous with second B-29. The weather reports received by radio indicated good weather at Kokura (3/10 low clouds, no intermediate or high clouds, and forecast of improving conditions). The weather reports for Nagasaki were good but increasing cloudiness was forecast. For this reason the primary target was selected.
1044 Arrived initial point and started bombing runs on target. Target was obscured by heavy ground haze and smoke. Two additional

runs were made hoping that the target might be picked up after closer observations. However, at no time was the aiming point seen. It was then decided to proceed to Nagasaki after approximately 45 minutes spent in the target area.

1150 Arrived in Nagasaki target area. Approach to target was entirely by radar. At 1150 the bomb was dropped after a 20 second visual bombing run. The bomb functioned normally in all respects.

1205 Departed for Okinawa after having circled smoke column. Lack of available gasoline caused by an inoperative bomb bay tank booster pump forced decision to land at Okinawa before returning to Tinian.

1351 Landed at Yontan Field, Okinawa

1706 Departed Okinawa for Tinian

2245 Landed at Tinian

Because of bad weather good photo reconnaissance pictures were not obtained until almost a week after the Nagasaki mission. They showed 44 per cent of the city destroyed; the discrepancy in results between this mission and the first was explained by the unfavorable contours of the city.

19.21 Exchange of information between Tinian and Los Alamos was extremely unsatisfactory and caused considerable difficulty at each end. Necessarily tight security rules made direct communications impossible, and teletype messages were relayed from one place to the other through the Washington Liaison Office, using an elaborate table of codes prepared by Project Alberta. Late in July, the Laboratory sent Manley to the Washington Liaison Office in an attempt to make sure that there would be no friction in the regular channels of information, and that no information was being held up in Washington which would conceivably be of interest. The first news of the Hiroshima drop came to Los Alamos in a dramatic teletype prepared by Manley summarizing the messages sent by Parsons from the plane after the drop (see Appendix No. 2).

19.22 On the day following the Nagasaki mission, the Japanese initiated surrender negotiations and further activity in preparing active units was suspended. The entire project was maintained in a state of complete readiness for further assemblies in the event of a failure in the peace negotiations. It was planned to return all Project Alberta technical personnel to the United States on August 20, except for those assigned to the Farrell mission for investigating the results of the bombing in Japan. Because of the delays in surrender procedures, Gen. Groves requested all key personnel to remain at Tinian until the success of the occupation of Japan was assured. The scientific and technical personnel finally received authorization and left Tinian on September 7, except for Col. Kirkpatrick and Cmdr. Ashworth who remained to make final disposition of project property. With this departure the activities of Project Alberta were terminated.

19.23 The objective of Project Alberta was to assure the successful combat use of an atomic bomb at the earliest possible date after a field test of an atomic explosion and after the availability of the necessary nuclear material. This objective was accomplished. The first combat bomb was ready for use against the enemy within 17 days after the Trinity test, and almost all of the intervening time was spent in accumulating additional active material for making another bomb. The first atomic bomb was prepared for combat use against the enemy on August 2, within four days of the time of the delivery of all of the active material needed for that bomb. Actual combat use was delayed until August 6 only by bad weather over Japan. The second bomb was used in combat only three days after the first, although it was a completely different model and one much more difficult to assemble.

Chapter XX

CONCLUSION

20.1 After the end of the war the Laboratory experienced a sudden relaxation of activities. Everything had been aimed at a goal, and the goal had been reached. It was a time for evaluation and stock-taking. Plans for the future of Los Alamos and of nuclear research in general were widely discussed. Members of the Scientific Panel of the President's Interim Committee on Atomic Energy met at Los Alamos and prepared for the Committee an account of the technical possibilities then apparent in the atomic energy field. A series of lecture courses was organized, called the "Los Alamos University," to give the younger staff members the opportunity to make up for some of the studies they had missed during the war years.

20.2 While research projects that had been under way at the end of the war were being completed, plans for the period to follow were being formulated. Although their discussion leads beyond the period of the present report, one that may be mentioned was the outlining and writing of a Los Alamos Technical Series, under the editorship of H. A. Bethe, to set down a more systematic and polished record of the Laboratory's work than had been possible during the war. There was some concentration of effort to complete the theoretical investigations of the Super described in Chapter 13. Weapon production had to continue, and plans were made to finish the development work on the implosion bomb (11.2).

20.3 This history has been an account of problems and their solution, of work done. The other side of the history of Los Alamos, the reactions of these accomplishments upon the people who made them, is present only by implication. This account ends at a time, however, when these reactions assumed a sudden importance, and it is appropriate that it should end with some description of them.

20.4 For many members of the Laboratory the Trinity test marked the successful climax of years of intensive and uncertain effort. A new kind of weapon had been made, and the magnitude and qualitative features of its operation had been successfully predicted. Despite the fact, perhaps in part because of the fact, that the explosion occurred as expected, the sight of it was a stunning experience to its creators, an experience of satisfaction and of fear. A new force had been created, and would henceforth lead a life of its own, independent of the will of those who made it. Only at Trinity, perhaps, were its magnitude and unpredictable potentialities fully grasped and appreciated.

20.5 Four days after the first bomb was dropped over Hiroshima, the Japanese began surrender negotiations. The feelings that had marked the success of the Trinity test were evident once more. But now the Laboratory, experiencing the sudden slackening of effort that followed the end of the war, began to speak seriously of the bomb and its consequences for the future. The thoughts that were expressed were not new, but there had been no time before to express them. Since 1939, when the decision had been made to seek Government support for the new development, a uniformity of insight had grown up among the working scientists of the Manhattan District. They had come to realize that atomic warfare would prove unendurable. This was learned by the Japanese in the days of Hiroshima and Nagasaki, and soon all the world was saying it.

20.6 What the members of the Laboratory saw who joined in these discussions was more incisive than this. Atomic bombs were offensive or retaliatory weapons, their existence was a threat to the security of every nation which it could not venture, without the gravest risk, to meet on the military plane alone. The law of counterdevelopment, which has so uniformly in military affairs operated to produce new defenses against new weapons, could in this case operate to open channels of collaboration that have not previously existed among nations. The wartime scientific collaboration that had produced this weapon could, by its worldwide extension, be made uniquely the means for eliminating it from national armaments. Men of science, who had as a group never been concerned with the problems of society and of nations, felt responsible to tell the American public of the nature and implications of the new weapon, and to make clear the alternatives for the future that had arisen. This concern received perhaps its best and simplest expression in a speech by Oppenheimer, given on October 16, 1945, when the Laboratory was presented by General Groves with a certificate of Appreciation from the Secretary of War:

20.7 "It is with appreciation and gratitude that I accept from you this scroll for the Los Alamos Laboratory, for the men and women whose work and whose hearts have made it. It is our hope that in years to come we may look at this scroll, and all that it signifies, with pride.

"Today that pride must be tempered with a profound concern. If atomic bombs are to be added as new weapons to the arsenals of a warring world, or to the arsenals of nations preparing for war, then the time will come when mankind will curse the names of Los Alamos and Hiroshima.

"The peoples of this world must unite, or they will perish. This war, that has ravaged so much of the earth, has written these words. The atomic bomb has spelled them out for all men to understand. Other men have spoken them, in other times, of other wars, of other weapons. They have not prevailed. There are some, misled by a false sense of human history, who hold that they will not prevail today. It is not for us to believe that. By our works we are committed, committed to a world united, before this common peril, in law, and in humanity."

NR 137
FROM WASH LIAISON OFC WASH DC AUG 45..0402
TO COMMANDING OFFICER CLEAR CREEK
FIVE PARTS - TART ONE
SW
KC

FLASHED FROM THE PLANE BY PARSONS ONE FIVE MINUTES AFTER RELEASE
AND RELAYED HERE WAS THIS INFORMATION QUOTE PAREN REF EIDM WL
TO OPPENHEIMER FROM GENERAL GROVES THIS RESUME OF MSSSAGES PREPARED
BY DOCTOR MANLEY PAREN CLEAJ CUT RESULTS COMMA IN ALL RESPECTS SUCCES
FUL PD EXCEEDED TR TEST IN VISIBLE EFFECTS PD NORMAL CONDITINXXXXXX
CONDITIONS OBTAINED IN AIRCRAFT AFTER DELIVERY WAS ACCOMPLISHED PD
VISUAL ATTACK ON HIROSHIMA AT ZERO FIVE TWO THREE ONE FIVE Z WITH
ONLY ONE TENTH CLOUD COVER PD FLACK AND FIGHTERS ABSENT UNQUOTE AFTER
RTXXXXX RETURN TO BASE AND GENERAL INTERROGATION FARRELL SENT THE
FOLLOWIGXXXX FOLLOWING INFORMATION QUOTE ALARGE OPENING IN CLOUD
COVER DIRECTLY OVER TARGET MADE BOMBING FAVORABLE PD EXCELLENT RECORD
REPORTED FROM FASTAX PD FILMS NOT YET PROCESSED BUT OTHER OBSERVING
[illegible]SOALSO ANTICIPATE GOOD TREXXXX RECORDS NXX PD NO APPRE
JQXD 3CFA
R NIL
K HOW MANY LINES DID U GET
R 12 LINWA
PLANES ALSO ANTICIPATE GOOD RCXXX RECORDS PD NO APPRECIABLE NOTICE OF
SOUND PD BRIGHT DAYLIGHT CAUSED FLASH TO BE LESS BLINDING THAN TRPXXX
TR PD A BALL OF FIRE CHANGED IN A FEW RECORDS TO PURPLE CLOUDS AND
BOILING AND UPWARD SWIRLING FLAMES PD TURN JUST COMPLETED WHEN FLASH
WAS AXXX OBSERVED PD INTENSLY BRIGHT LIGHT CONCEALED BY ALL AND RATE
OF RISE OF WHITE CLOUD FASTER THAN AT TR PD IT WAS ONE THIRD GREATER
IN DIAMETER REACHING THIRTY THOUSAND FEET IN THREE MINUTES PD MAXIMUM
ALTITUDE AT LEAST FORTY THOUSAND FEET WITH FLATTENED TOP AT THIS
LEVEL PD COMBAT AIRPLANE THREE HUNDRED SIXTY THREE MILES AWAY AT
[illegible]THOUSAND FEET OBSERVEDIT PD D
NIL AGN
.3 OK OPR WELL JUST HAVE TO KEEP TRING AS THESE MESSAGES AR IMP
MIN PLS
OPR U STARTED THIS MSG AS PART TWO ISNT IT PART OF PART ONE
M MIN OPR I TOLD U I WD START PART TWO WHERE PART ONE NILED
IS THAT CLEAR

BUT OPR I DIDNT GET PART ONE COMPLETE

AND THE I TOLD TO U TO SA START WITH 12 LINE
AND THE 12 LINE U L O WELL I THOT U MEANT U GOT 12 OK
M THIS IS A AWFUL MESS ISNT IT IT SH SURE IS DOU THINMI WNGEFG

MIN PLS
TRY ANOTHER MACHINE MAYBE IT WILL DO VETTER
OPR IT ISNT UG MACH AND I KNOW IT IT S MINE AND THERE ISNT
A THING CAN BE DONE AS THE REPAIR MAN SAYS THERE ISNT ANYTHING WRONG
WITH IT HES BEEN HERE ALL DAY AND THIS IS AS GOOD AS IT WAILL RUN
I HAVE LOADS TO GO UXX TO U TONIGHT BUT WELL HAVE TO DO IT THIS WAY
A FEW LINES AT A TIME MIN I WANT TO TALK TO THE LT A MIN
OK
OPR ILL CALL U BACK IN A BT 10 MINUTES
.1OK

APPENDIX NUMBER 4

TRINITY PROJECT DETAIL LOCATION PLAN

Station	Group Leader	Symbol
Piezo Gauge	Walker	×
Sentinel (Type A)	Moon	⊛
Sentinel (Type B)	Moon	✱
Geophone	Houghton	◬
Paper Box Gauge	Hoogterp	⊡
Flash Bomb	Mack	◩
R 4 Ground Station	Segrè	⊠
R 4 Balloon Winch	Segrè	⚲
E. D. G.	Moon	‡
Mack Slit Camera	Mack	ዩ
Impulse Meter	Jorgensen	◓
Condenser Gauge	Bright	⧗
Excess Velocity Gauge	Barschall	⊕
Tank Range Poles	Anderson	⚠
Tank Flag Poles	Anderson	⚑
Primacord Station	Mack	⚳
Metal Stake (Earth Disp)	Penney	○
Piezo Gauge Amplifier	Walker	◎
Balloon	Richards	♀
Balloon Winch	Richards	⊖
Ground Station	Richards	⌖

Roads ═══ ═══ ═══ ═══

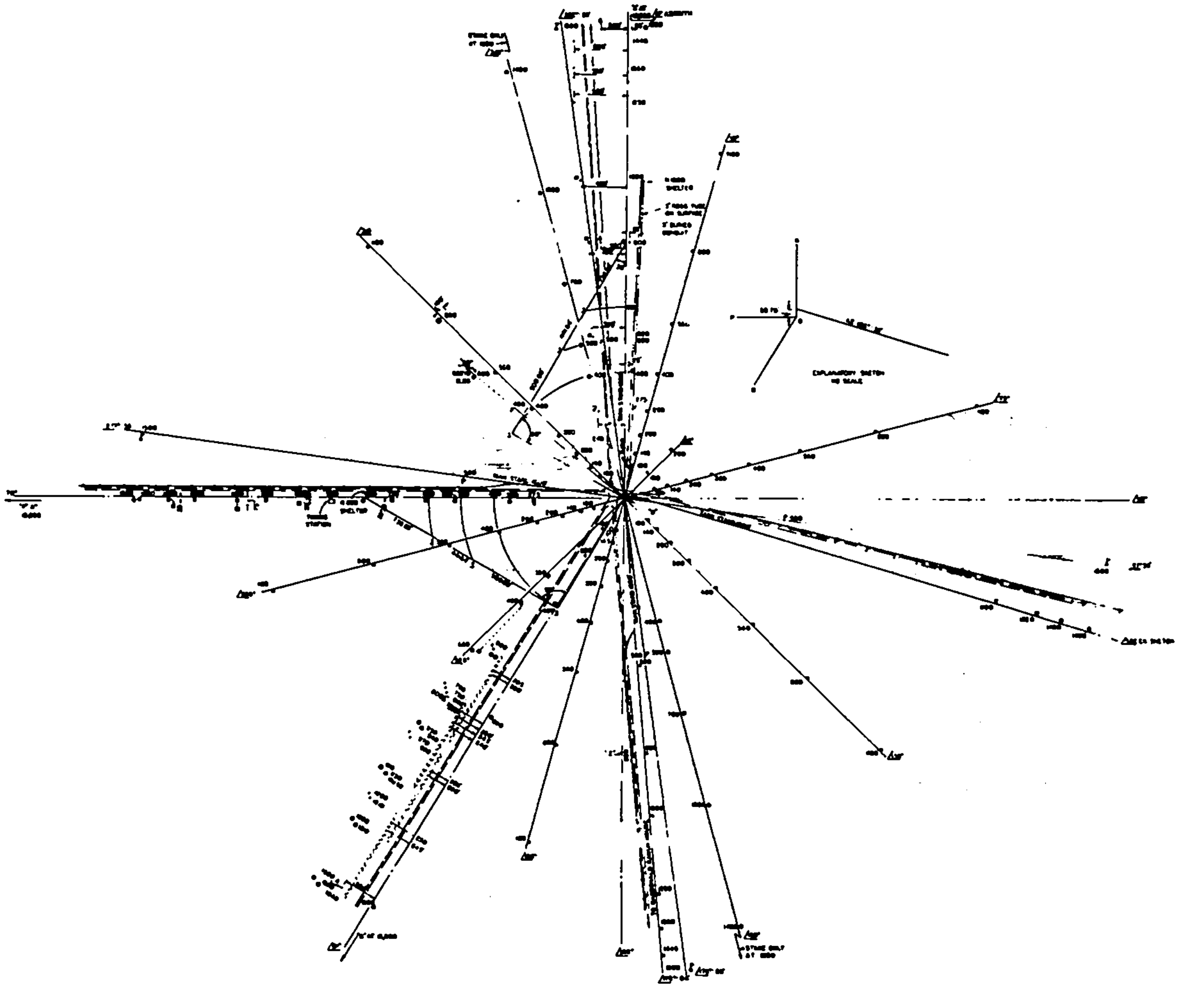
Buried Wires or Cables — — — — — — — —

Center Lines - ———— - ———— - ———— -

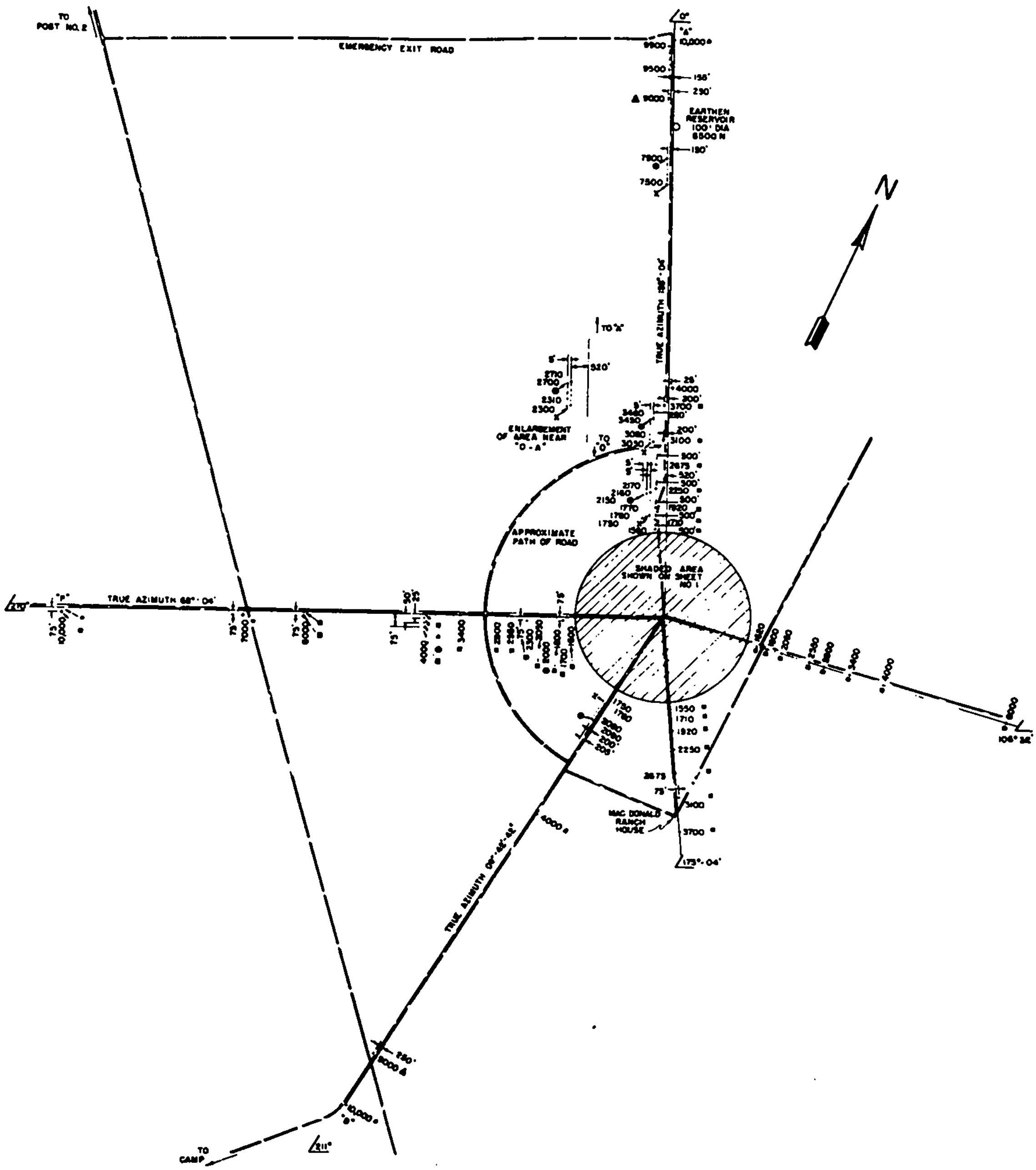
Tank Right of Way ┴┬┴┬┴┬┴┬┴┬┴

Note: Angles are Azimuths on "OA" Line
Distances thus (800) are Radial Yards from "O"
Distances thus (75') are Offsets from L of Roads and Center Lines.

Scale: 1500 Yard circle - 1" = 300 Yards. - Sheet 1
10,000 Yards - 1" = 2750 Yards. - Sheet A



Sheet 1


TO POST NO. 2
EMERGENCY EXIT ROAD
EARTHEN RESERVOIR 100' DIA 8500 N
TRUE AZIMUTH 68°-04'
APPROXIMATE PATH OF ROAD
SHADED AREA SHOWN ON SHEET NO 1
ENLARGEMENT OF AREA NEAR "O-A"
MAC DONALD RANCH HOUSE
TO CAMP
N

Sheet A

GLOSSARY OF TERMS

(α, n) Reaction. Any nuclear reaction in which an alpha particle (helium nucleus) is absorbed by a nucleus, with subsequent emission of a neutron.

Autocatalytic Assembly. Any method of assembling supercritical amounts of nuclear explosive, in which the initial stages of the explosion are made to assist the further assembly of the explosive. e.g., by expulsion or compression of neutron absorbers placed in the active material.

Baratol. A castable explosive mixture of barium nitrate and TNT.

Baronal. A castable explosive mixture of barium nitrate, TNT, and aluminum.

Betatron. Induction electron accelerator for generating electron beams of very great energies.

Branching Ratio. The ratio of the capture cross section to the fission cross section.

Cockcroft-Walton Accelerator. An accelerator using voltage multiplication of the rectified output of a high voltage transformer to obtain a high potential.

Composition B. A castable explosive mixture containing RDX, TNT, and wax in the proportion 60/40/1.

Critical Mass. That amount of fissionable material which, under the particular conditions, will produce fission neutrons at a rate just equal to the rate at which they are lost by absorption (without fission) or diffusion out of the mass.

Tamped Critical Mass. The critical mass when the active material is surrounded by a tamper.

Critical Radius. The radius of a spherical arrangement of fissionable material equal to one critical mass under existing conditions.

Cross Section. A quantitative measure of the probability per particle of the occurrence of a given nuclear reaction. It is defined as the number of nuclear reactions of a given type that occur, divided by the number of target nuclei per square centimeter and by the number of incident particles.

Absorption Cross Section. The cross section for the absorption of a neutron by a given nucleus.

Capture Cross Section. The cross section for the (n, γ) reaction, in which a neutron is absorbed by a nucleus, with subsequent emission of gamma radiation.

Fission Cross Section. The cross section for the absorption of a neutron, followed by fission.

Scattering Cross Section. The cross section for the scattering of a neutron by the nuclei of some target material. Since scattering is a quantitative matter, the definition is incomplete. The differential scattering cross section is the cross section for scattering at an angle between θ and $\theta + d\theta$. The transport cross section is an average or integral scattering cross section, so defined as to give the average scattering in the forward direction:

$$\sigma_T = 2\pi \int_0^{\pi} (1 - \sin \theta)\, \sigma_s(\theta) \sin \theta \, d\theta$$

where $\sigma_s(\theta)$ is the differential scattering cross section defined above.

Cyclotron. Magnetic resonance accelerator, used in investigating atomic structures.

D(d, n) Reaction. The nuclear reaction produced by bombarding deuterons with deuterons, producing high energy neutrons.

D-D Source. The above reaction used as a source of high energy neutrons. At Los Alamos, the Cockcroft-Walton accelerator was principally used for this purpose.

Deuterium. Heavy hydrogen, D_2 or H_2^2, the hydrogen isotope of mass two.

Deuteron. A nucleus of deuterium or heavy hydrogen.

Electron Volt. An electron volt is the energy acquired by an electron falling through a potential of 1 volt. One electron volt is about 1.6×10^{-12} ergs. In thermodynamic units, 1 electron volt corresponds to a temperature of about 12,000 degrees absolute. Thus a fortieth of a volt per particle corresponds to "room temperature." Energies of this order are called "thermal." One million electron volts corresponded to a temperature of 1.2×10^{10} degrees absolute.

Fission Spectrum. The spectrum, or energy distribution, of neutrons emitted in the fission process.

Inelastic Scattering. The scattering of neutrons in which energy is lost to excitation of target nuclei.

Li(p, n) Reaction. The nuclear reaction in which neutrons are produced by bombardment of lithium by protons.

Neutron Number. The number of neutrons emitted per fission. This number is statistically variable; the expression refers therefore to the average number per fission.

(n, γ) reaction. A nuclear reaction in which a neutron is captured by a nucleus, with subsequent emission of gamma radiation.

PETN. Pentaerythritol tetranitrate.

RDX. Cyclotrimethylenetrinitramine.

Thermonuclear reaction. A mass nuclear reaction induced by thermal agitation of the reactant nuclei. The reaction is self-sustaining if the energy release is sufficient to counter-balance the energy losses that may be involved.

Tamper. A neutron reflector placed around a mass of fissionable material to decrease the neutron loss rate.

Taylor Instability. A hydrodynamical principle which states that when a light material pushes against a heavy one, the interface between them is unstable, and that when a heavy material pushes against a light one, the interface is stable.

Tritium. The hydrogen isotope of mass three. This isotope was discovered in the Cavendish Laboratory by Oliphant in 1934. It was there produced by deuterium-deuterium bombardment. Tritium is a radioactive gas with a half-life of about twenty years.

Triton. A nucleus of tritium.

Thermal Neutrons. Neutrons of thermal energy - see Electron Volt.

T-D Reaction. The nuclear reaction of tritons with deuterons.

Torpex. A castable explosive mixture of RDX, TNT, and aluminum.

Van de Graaff Generator. An accelerator using the electrostatic charge collected on a mechanically driven belt to obtain a high potential.